11 Clinical Assessment of Nasal Airway Obstruction

Ethem Sahin, Burak Çakır, and Klaus Vogt

11.1 Introduction

For the evaluation of nasal airway obstruction physical examination, anterior rhinoscopy, laboratory workup, imaging studies, and rhinomanometric studies may be required. Laboratory workup may consist of counts of neutrophil investigating infectious diseases, eosinophil for allergy-related disorders, and mast cell in food allergy. Imaging workup contains computed tomography (CT) and magnetic resonance imaging. Physically based studies involve rhinomanometry and acoustic rhinometry (AR) techniques [1].

11.2 Nasal Resistance

Nasal resistance is responsible for more than 50% of the resistance of the total airway [2]. The nasal cavity is designed like two parallel resistors [3, 4]. The nasal vestibule, nasal valve, and nasal cavum are the three components that form the resistance in the nose [2]. The nasal valve is the main restricting part of the airflow, and is outlined by the inferior border of the upper lateral cartilages intersecting the caudal part of the inferior turbinates beside the septum [2]. The angle between the septum and the upper lateral cartilage is 10–15° [5], which may vary due to ethnic differences. The nasal valve is usually located less than 2 cm distal in the nasal passageway, approximately 1.3 cm from the naris. The average cross-sectional area is 0.73 cm^2 [2].

Nasal resistance is made up of two layers: the deeper layer consists of underlying bone, cartilage, and muscle, while superficially the overlying mucosa forms the second layer. Environmental and intrinsic conditions both alter nasal resistance. Variables reducing resistance consist of sympathomimetics, atrophic rhinitis, exercise, rebreathing, along with erect posture [3]. Exercise leads to sympathetic vasoconstriction and shrinkage of the ala nasi, dilating the nasal cavities [1]. Infectious rhinitis, vasomotor rhinitis, allergic rhinitis, supine posture, hyperventilation, cold air, aspirin, and alcohol increase nasal resistance [6].

The vestibule acts as the initial area of nasal resistance. It is made up of compliant walls, which are likely to collapse from the negative pressures that are produced in inspiration. The nasal vestibule is actually called as the external nasal valve. Research has demonstrated that an airflow rate of 30 L/min or higher can result in the collapse of the nasal airway during inspiration in this region. Laterally, the vestibule is mainly maintained by the alar cartilage and musculofibrous attachments. Though the vestibule tends to collapse in inspiration, the patency of the nasal passage is maintained by the work of the dilator naris muscles. While in expiration, vestibule dilates with the positive pressure [3].

A significant region for resistance takes place at the caudal border of the inferior turbinate within the access to the pyriform aperture. This critical region is referred to as the internal nasal valve. Overall, the nasal valve area involves the inferior border of the upper lateral cartilage, the head of the inferior turbinate, the floor of the nose, the caudal septum, the frontal process of the maxilla, the pyriform aperture, and the lateral fibrofatty tissue and forms the narrowest portion of the airway [3, 4].

It should be emphasized that the terms "external valve" and "internal valve" are acceptable only if they are used within an anatomical context. From the functional point of view, only one nasal valve is existing as the entire complex of elastic structures at the nasal entrance. Recent research and development of nasal airway function tests are directed on quantifying the relation between nasal air stream and nasal valve movement.

Facial nerve paralysis can cause a loss of active contraction and contribute to airway obstruction. In suspected facial nerve

E. Sahin (✉)
Department of Otorhinolaryngology, Bayindir Içerenköy Hospital, Istanbul, Turkey
e-mail: esahin@bayindirhastanesi.com.tr

B. Çakır
Department of Otorhinolaryngology, Beykent University, İstanbul, Turkey

K. Vogt
Faculty of Medicine, Centre of Experimental Surgery, University of Latvia, Riga, Latvia

C. Cingi, N. Bayar Muluk (eds.), *All Around the Nose*, https://doi.org/10.1007/978-3-030-21217-9_11

damage, the activity of the alae nasi muscle may be tested [7]. The loss of innervation can result in alar collapse even in quiet respiration. The voluntary flaring of the naris has long been associated with a potential 20% diminishment in the resistance, demonstrating the role of facial nerve in the nasal resistance [3]. The active contribution of the dilator naris happens in the course of exercise, minimizing airway resistance [8].

11.3 Fluid Mechanics of Nasal Airflow

Understanding the fluid dynamics of the nose as a part of nasal physiology means first to understand some basic facts:

1. The nose is an irregular rigid streaming body with elastic or movable compartments on both ends, that is, the nasal valve and the pharynx.
2. The timeline of pressure and flow is representing an irregular wave as in the overall airway. The air stream is almost unsteady, what means that it is quickly changing the speed as well as the direction. It follows that these parameters can be measured at any time but not simply calculated or predicted.
3. The nasal airstream is always in part turbulent and laminar, which can easily be shown by computational fluid dynamics (CFD). The relation between laminar and turbulent parts is changing during one breath. Therefore, the nasal airstream cannot be generally described by a simple formula.
4. Measurements of pressure and flow through the nose are integrating the airway between the anterior and posterior end, while a determination of laminar and turbulent parts of the airflow within the nose and local variations inside the nasal cavity can only be determined by CFD (Fig. 11.1).

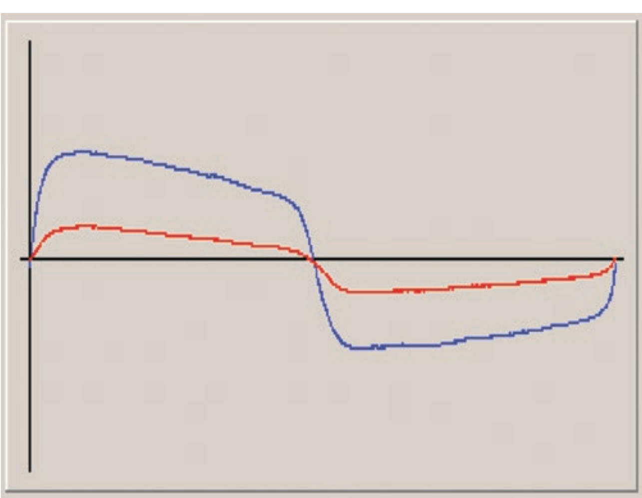

Fig. 11.1 Typical nasal breathing curve (Courtesy of Klaus Vogt)

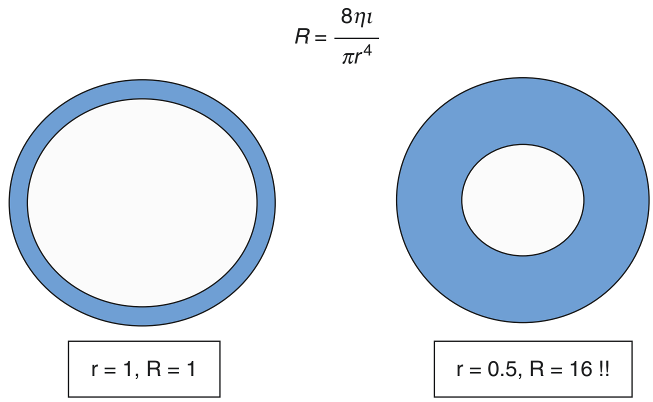

Fig. 11.2 The law of Hagen–Poiseuille (Courtesy of Klaus Vogt)

To better understand the relations between form and resistance of the nasal air channel, one of the basic laws in fluid dynamics is very helpful. The law of Hagen–Poiseuille is valid for the resistance of round tubes, which means that in a tube, the resistance R increases linear with the viscosity of the fluid and the length of the tube but with the 4 power of the tube radius. Reducing the radius to the half leads to a 16-fold increase of resistance! (Fig. 11.2).

$$r = 0.5, R = 16!!$$

The law applies also as an approximation for irregular cross-section areas as we find in the nose. It is also responsible for the fact, that the human eye cannot estimate the consequences of a narrowed airway as for instance also in the larynx or trachea. Also, a linear correlation does not exist between the results of acoustic rhinometry and rhinomanometry.

11.4 Assessment of Nasal Obstruction

11.4.1 History

Patient background and assessment of signs and symptoms along with physical examination is the basis of the diagnosis of nasal obstruction. This history includes the characteristics of nasal obstruction/congestion; the occurrence of other symptoms of rhinosinusitis, like postnasal discharge, itching, sneezing, and ocular symptoms; associated signs, like pain, in the face and head, lack of smell sensation; as well as related data (length of the symptoms, pattern in time, and triggering events) [9].

The causes of nasal obstruction are listed below [2]:

- Deviation of the nasal septum
- Turbinate hypertrophy
- Rhinoplasty
- Collapse of the nasal valve

- Choanal atresia
- Neoplasm
- Allergic rhinitis
- Polyposis
- Sinusitis
- Vasomotor rhinitis
- Rhinitis medicamentosa
- Septal perforation
- Septal hematoma

Mucosal vasodilation due to histamine discharge causes nasal congestion. Inflammation and discharge as a result of sinusitis can lead to stuffed nose. Deviation of the septum is a frequent source of blockage. The size of turbinates is crucial due to the fact that 50% of the airflow occurs in the middle segment of the air passage. Turbinates, which are alongside a perforated nasal septum, possibly get hypertrophied due to the turbulence of air in the nasal passage, leading to an additional airway resistance. Valvular collapse secondary to lack of cartilaginous reinforcement can result in nasal blockage. Moreover, rhinoplasty can be an important factor in iatrogenic nasal obstruction [1].

11.4.2 Rhinoscopy and Endoscopic Evaluation

Anterior rhinoscopy is a procedure that can be easily done using an otoscope or a nasal speculum and headlight, nevertheless, it gives inadequate information for diagnosis. It may be suitable in extreme cases or significant alterations appear in the condition of the patient [10, 11]. A basic assessment of the degree of nasal obstruction may be possible by having the patient exhale air from the nasal passage to a cold metal. Definitive diagnosis should be made by a specialist via endoscopic examination [12]. When chronic or persistent rhinosinusitis with or without polyps is diagnosed, follow-up evaluation is required after 4 weeks of therapy [9].

The outcomes of endoscopic assessments may be quantified with different rating scales, which consist of numeric ratings of edema, discharge/rhinorrhea, polyps, adhesions, or scars as well as crusting [13]. For instance, a scale for staging polyps may be 0 = none; 1 = within middle meatus; 2 = outside middle meatus yet not totally obstructing the nose; and 3 = total obstruction [9, 13].

11.4.3 Imaging

Obtaining routine CT scans and MRI in order to evaluate nasal blockage is not justified, though these imaging techniques are occasionally recommended for challenging cases, like the suspicion of a neoplasia [12]. CT scan-related staging may not quite correlate with symptoms of the disease [14]. MRI is often extra sensitive for the assessment of diseases of the sinus mucosa. Incidental information of abnormal mucosal alterations in patients having MRI for non-rhinologic conditions is actually mentioned in 31.7–55% of patients [15].

11.4.4 Objective Tests for Nasal Patency

Nasal blockage is a subjective discomfort arising from physiologic and pathological alterations, which are not foreseen. If the side difference of nasal resistance between two sides is <60–70%, it is most difficult for the patient to logically detect the more obstructed side [16].

Objective tests defining the volume nasal airflow are required for the evaluation of the patency for diagnostic, documentation, and medicolegal purposes. The most frequently used techniques identified are active anterior and posterior rhinomanometry (AAR, APR), and acoustic rhinometry (AR) [17].

11.4.4.1 Rhinomanometry (AAR, APR)

In 1965, Masing [18] stated the value of nasal resistance in the objective assessment and diagnosis of nasal obstruction. In 1968, Cottle [19] introduced passive anterior rhinomanometry (PAR). Additional improvement [20] of the procedure came about with the use of the Fleisch [21] pneumotachograph. This pneumotachograph, which displayed an adequate rise time of 0.018 s and a linear behavior up to 20 Hz, could actually document the respiratory airflow in time correctly. When pressure transducers could record the matching pressure changes, documentation of the two essential parameters of airflow, namely, the flow in cubic centimeters per second (cm^3/s) and pressure in Pascals (Pa), was possible. With the development of computer technology, the transduced electronic analog signals are digitalized and refined [22]. With this technology being established, AAR was finally feasible [17].

In 1984, the "International Standardization Committee for the Objective Assessment of the upper airway as a group of the European Rhinologic Society" published the following recommendations for rhinomanometric measurements:

> Using the mirror image screen, recordings from the right and left nasal cavity are displayed on a single graph, with "quadrants II (left upper quadrant) and IV (right under quadrant) for the left side and I (right upper quadrant) and III (left under quadrant) for the right side. The flow is plotted on the ordinate or *Y* axis, the pressure on the abscissa or *X* axis." The negative pressure is drawn on the right of the origin [17, 23]. The units that are utilized need to be SI units (cm^3/s for the flow and Pa for pressure gradient). Resistance is constantly determined at a fixed pressure of 150 Pa. If not, the reference pressure should be stated [17].

These recommendations are relating on the state of art in techniques at a time, when so-called graphical xy-recorders have been used and the point to be measured was determined by pen and ruler. By using one-point measurements, essential information of the complete measurement series is lost. One-point measurements are not correlated with the subjective sensing of obstruction. The calculation of a linear resistance at the fixed pressure of 150 Pa is mathematical nonsense, because such a relation exists only at the top of the breathing curve: it is the vertex resistance (VR).

In the late 1980s, the first microprocessor-controlled and later on software-based rhinomanometers came to the market. If recorded in the standard X–Y mirror image, a phase shift is observed during cyclic breathing between flow and pressure gradients that results in hysteresis. This phenomenon was always considered an artifact of the apparatus due to the different properties of the transducers. This problem can be solved by adapting a numerical function, and as a consequence, a regression line is recorded instead of a loop. Vogt et al. [24] claimed that this phase shift is not an artifact but due to a characteristic behavior of the nasal airstream. Consequently, the general shape of the rhinomanometric function does not correspond to a single s-shaped curve through the X–Y axis intersection (origin) but rather a double loop that crosses both axes outside the origin. The phase shift between the pressure gradient and flow is caused by:

– Compressibility of the air and inertia of the airstream
– Elasticity of the anatomical structures [24].

If one considers the timeline for pressure and flow as shown in Fig. 11.3, then it is obvious that the ascending and descending curve parts cannot be identical: analyzing the wave instead of an incorrect regression line was first published by Vogt et al. as "High Resolution Rhinomanometry" and, after the consensus conference of the ISOANA in 2003, renamed as "4-phase rhinomanometry" (4PR).

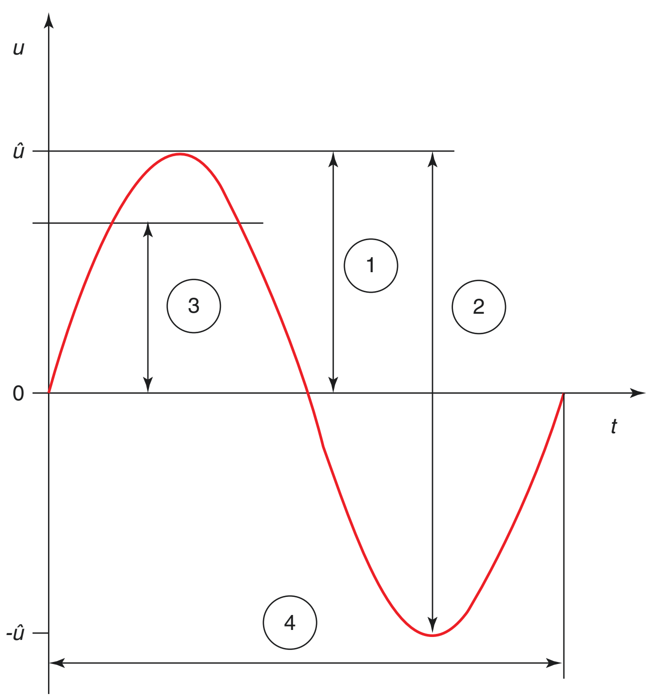

Fig. 11.3 Parameters of voltage in an electric sinus wave. 1 = peak value, vertex value, amplitude; 2 = peak-valley distance; 3 = effective value, RMS; 4 = time of a period (Courtesy of Klaus Vogt)

The substantial differences between the "classic" and the 4-phase rhinomanometry are:

1. Analyzing the entire breath instead of single points of the breathing curve
2. Creating measured parameters as indicators for the energetic of nasal breathing instead of estimations derived from single measured points
3. The logarithmic transformation of the measured parameters with the consequence of a significant correlation with the sensing of obstruction
4. A visual information about the influence of the nasal valve.

The numerical evaluation of the nasal valve is presently a matter of ongoing research.

Breathing waves follow the same rules as electromagnetic waves. They are simply slower and asymmetric. Thus, we can apply the physics and laws of electricity. The voltage of 230 V as daily measured in power stations or in the sockets of every household is the "effective voltage" or in English root mean square (RMS) and the power intensity is the "effective intensity." These parameters have been introduced by Vogt and Hoffrichter in 1994 within the context of 4PR.

Figure 11.3 explains that we are dealing of the nasal air stream with very similar processes as in electro engineering when measuring parameters:

In statistics, the **root mean square** (abbreviated *RMS* or *rms*), also known as the *quadratic mean*, is a statistical measure defined as the square root of the arithmetic mean of the squares of a set of numbers. It is of utmost importance that this value may be calculated for a continuously varying function as breathing waves as well.

In the case of a set of n values $\{x_1, x_2, \cdots x_n\}$, RMS is calculated as:

$$x_{\text{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}$$

In the practice of 4PR, RMS for pressure and flow is calculated from all measured values during the data acquisition process thus obtaining correct *measured* values instead of weak estimations.

Finally, there are two measurable and reliable parameters, which inform us about the energetics of the nasal air stream: effective resistance (Reff) and vertex resistance (VR). The effective resistance can be measured through the entire breath, inspiration, or expiration; vertex resistance can be determined in inspiration and expiration. All parameters are highly correlated to each other except in cases of big loops as follow-up of valve phenomena.

Rhinomanometry and Subjective Sensation of Obstruction

In the course of last years, major international discussions centered around the question whether rhinomanometric measurements or other nasal function tests were related to the subjective sensation of the obstruction; the results were, however, controversial. A summary of results was given in 2009 by Andre et al. Nearly all of the cited authors as listed in this meta-analysis concluded that a statistically significant correlation between objective results and sensing of an obstruction does not exist. However, reasons for the missing relation have not really been found by interpretation; yet they are quite clear.

In psychophysics, the *Weber–Fechner law* combines two different laws of human perception, which both describe the ways in which the resolution of perception diminishes for stimuli of greater magnitude. Ernst Heinrich Weber (1795–1878) was one of the first to approach the study of the human response to a physical stimulus in a quantitative fashion. Weber found that the *just noticeable difference* (jnd) between two weights was approximately proportional to the weights. Thus, if the weight of 105 g can (only just) be distinguished from that of 100 g, the jnd (or differential threshold) is 5 g. If the mass is doubled, the differential threshold also doubles to 10 g, so that 210 g can be distinguished from 200 g. In this example, a weight (any weight) seems to have to increase by 5% for someone to be able to reliably detect the increase, and this minimum required fractional increase (of 5/100 of the original weight) is referred to as the "Weber fraction" for detecting changes in weight. Gustav Theodor Fechner (1801–1887), a scholar of Weber, later used Weber's findings to construct a psychophysical scale in which he described the relationship between the physical magnitude of a stimulus and its (subjectively) perceived intensity. *Fechner's law* (better referred to as Fechner's scale) states that subjective sensation is proportional to the logarithm of the stimulus intensity. Fechner's scaling has been mathematically formalized [25].

The feeling of impaired breathing through the nose is in fact the feeling of increased power, which is necessary for the work of breathing and the sensation of the cooling effect of the streaming air on the nasal mucosa. Both sensations are following these basic laws. Searching for statistic correlations between subjective and objective data needs the collection of subjective data by means of a visual analog scale (VAS) and to correlate them with the data of objective measurements. The distributions are normally visualized as "histograms" showing the frequency of a class.

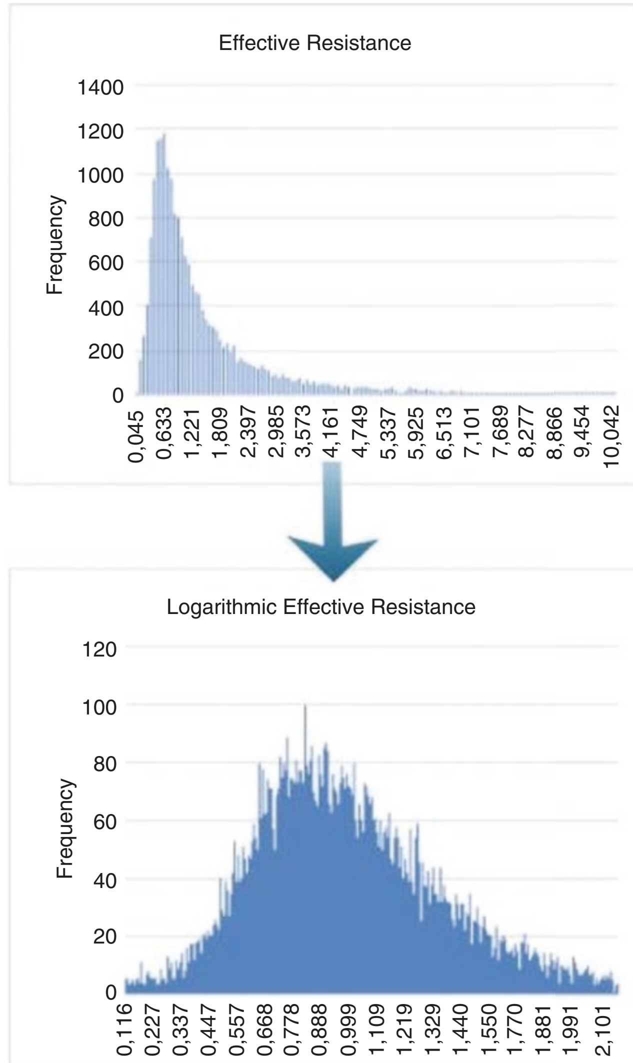

Fig. 11.4 Statistical distribution after logarithmic transformation of effective resistance (Courtesy of Klaus Vogt)

Figure 11.4 shows such histograms for the effective resistance in measurements. There is a higher incidence on the left side, which means that there are less patients with a "very good" nose while findings typical for an obstructed nose are much more varying on the right side. After logarithmic transformation, this typical distribution changes and approaches a so-called "normal distribution" or "Gauss distribution." The histogram of subjective measurements shows a "steady distribution": the number of patients is very similar in all classes.

The statistic relation between two distributions is given by the "correlation coefficient." Testing the correlation between subjective data and effective resistance as well as the data of the one-point measurements in three different studies showed that there is no significant correlation, but becomes significant after logarithmic transformation both for the effective resistances and for the VR [26].

For these reasons, logarithmic effective resistance and logarithmic vertex resistance as parameters were introduced in the daily clinical practice. Even if the measurement of the total nasal resistance is of marginal interest for the surgeon, an estimation providing clinical comparisons can be calculated by the equation of parallel resistors by the effective resistance of both sides.

Since small and negative numbers are difficult to handle, the logarithm of the tenfold value as basis for the classification of the nasal obstruction was introduced. These parameters have now been applied for 10 years in 20 countries worldwide. A retrospective analysis of 36,500 for the unilateral resistance and for in 10,300 cases for total resistance has led to the classification of nasal obstruction [26].

Four-Phase Rhinomanometry (4PR) and the Nasal Valve

Reviewing the recent rhinological literature, one may find many references mentioning the "nasal valve," but structured research about the complex function of the elastic structures at the nasal entrance cannot be found. We have to deal with the following facts:

1. The elevation of the negative nasal pressure by rapid inspiration for the removal of unwanted mucous and cleaning the paranasal sinuses is a normal function of human beings and may be called one of the "parafunctions" of the nose.
2. "Sniffing" means the creation of small eddies by under pressure: The valve function may also sometimes participate.

A non-physiological function or premature closure occurs, when so-called Bernoulli-effects get effective similar to flying, singing, or sailing and a dynamic narrowing of the nasal entrance induced by the airflow it selves occurs (Fig. 11.5). Such deformable resistors are known as "Starling resistors" in heart and lung physiology.

The specific issues of the nasal valve are:

- Asymmetry
- Changing speed and direction of airflow (unsteady airflow)
- Mechanical properties of rigid and elastic components
- Different shape of the air channel in inspiration and expiration

Along a breath, the valve reacts as follows:

- *Phase 1.* The inspiratory airstream is created and the intranasal pressure gets lower as the flow increases. The nasal wing approaches the septum.
- *Phase 2.* The nasal wing remains in the inside position as long as the flow is not diminished and moves outside in the lower flow. At the end of Phase 2, the start position is reached.
- *Phase 3.* During expiration, the pressure behind the narrowing cannot be diminished due to the infinite volume.
- *Phase 4.* The nasal wing returns to the start position.

Figure 11.6 shows a typical rhinomanometric graph with an expressed valve phenomenon.

Surgery of the nasal valve becomes more and more popular. Therefore, intensive research has to find quantitative parameters as well to characterize the mechanical properties of the nasal entrance as well as the influence of flow and acceleration of the nasal air stream. Also, the configuration and the topography of the compartments have to be analyzed in detail. It is very likely, that these problems may be solved by the aid of computational fluid dynamics.

In November 2016, the International Standardization Committee on the Objective Assessment of the Upper Airway (ISCOANA) confirmed the concept of four-phase rhinomanometry as the new international standard for rhinomanometry during an international interdisciplinary consensus conference [27].

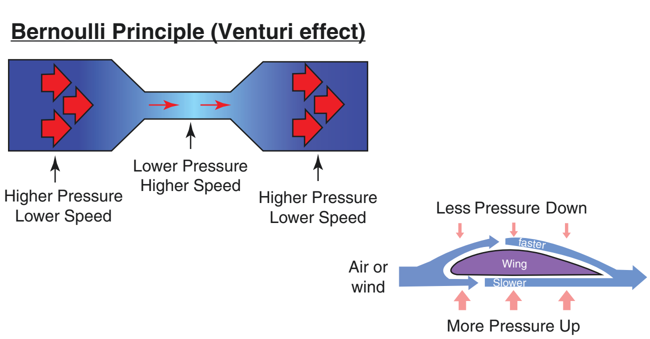

Fig. 11.5 Bernoulli effect (Courtesy of Klaus Vogt)

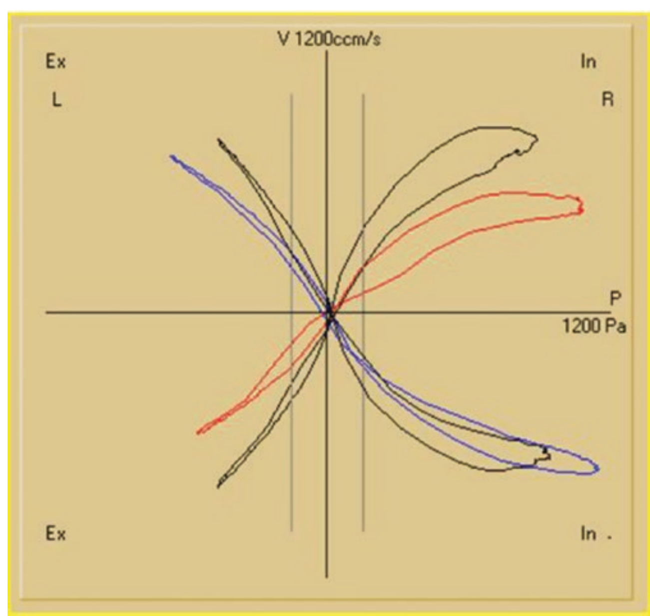

Fig. 11.6 Typical rhinomanometric graph (Courtesy of Klaus Vogt)

11.4.4.2 Acoustic Rhinometry

Acoustic rhinometry (AR) is one of important diagnostic tools in the objective analysis of nasal patency; it offers details on the geometry of nasal cavities with the help of acoustic (sound) waves, which are produced by the device. AR can identify narrow parts inside the nose, which can cause nasal obstruction. AR cannot give details on nasal respiratory function and cannot measure breathing, like rhinomanometry. The acoustic rhinometer produces an acoustic wave that is carried into one nostril via a tube. The dimensions and the pattern of the reflected sound waves give details about the structure and size of the nasal passage, with the time delay of reflections corresponding to the distance from the nostril. The transformation of echo measurements to nasal volume necessitates "mathematical calculations and theoretical assumptions" and is carried out by the computer, which is linked to the recording device. In a nose which is congested or blocked with nasal polyps or tumor, the narrowest parts can be found deeper in the nose, and AR can identify this place; nevertheless, it cannot distinguish the obstructing factor [28].

This technique is a simple and non-painful technique to complete. The individual is placed in an upright, blows the nose and puts the nose piece into the nose. The surrounding where AR is made must be standardized regarding humidity and temperature. Silence throughout the measurement is crucial. The nose piece must suit the nostril, providing an air-tight closure. Measurements are carried out also when holding breath [28].

As the measurements are conducted prior to and after spraying a topical decongestant into the nasal cavity; the changes within the cross-sectional diameter of the nose are generally ascribed to nasal mucosal congestion. Data, which are acquired following decongestion, are used for evaluating the anatomical components affecting the cross-sectional diameter of the nasal cavity [28].

Acoustic rhinometry enables "an assessment of the cross-sectional area of the nasal cavity as a function of the distance in the nose." Therefore, AR offers a two-dimensional image of the nasal cavity. In a non-decongested nose, "three deflections or minimum notches on the area-distance curve are seen." The narrowest portion of the nasal passage is commonly located within a range of 3 cm from the nostrils. Two minima have been defined in this area [29]. One deflection demonstrates the nasal valve (I-notch, which represents the isthmus nasi), and the other demonstrates the caudal end of the inferior turbinate (C-notch, which represents the head of the inferior turbinate) [30]. The initial notch might, actually, be artifactual [31]. "Amongst the two first minimum regions is usually the absolute minimum of the curve." In several subjects, the minimal cross-sectional area (MCA) matches the nasal valve while in other individuals, it matches the head of the inferior turbinate. A comparison of the region of the MCA in the identical subject prior to and following decongestion can be beneficial to figure out whether or not the MCA matches the nasal valve or the head of the inferior turbinate [23].

Acoustic rhinometry (AR) evaluates the nasal cross-sectional area (CSA) at various ranges from the nasal inlet utilizing acoustic reflections; it has been validated as an accurate, reproducible, and noninvasive technique [32, 33] that highly correlates with CT and MRI [32, 34–36]. In contrast to rhinomanometry, which presents a dynamic image of nasal airflow and resistance, AR offers a structural image of nasal airway dimensions and pattern [37]. AR permits "the determination of the cross-sectional area of the nose as a function of the distance in the nasal cavity." Therefore, AR offers "a two-dimensional image of the nasal cavity" [37]. The first notch, an "I-notch" or "C-notch," was suggested based on the concept of only one minimal MCA (Fig. 11.7) [38].

AR measures "the CSA with distance into the nasal cavity, showing three points of narrowing that present as minima on the plot of CSA: CSA1, CSA2, and CSA3. CSA1 indicates the internal nasal valve at the intersection of the upper lateral cartilage and nasal septum ~0.5–1.0 cm deeper from the nostril. CSA2 indicates to the narrowing at the head of the inferior turbinate ~2 cm deeper from the nostril. CSA3 is correlates the head of the middle turbinate and the caudal part of the inferior turbinate ~4 cm from the nostril. The narrowings at CSA1 and CSA2 on the graph sometimes are labeled I-notch (for isthmus nasi) and C-notch (for concha inferior), respectively" (Fig. 11.8) [9, 32].

For acoustic rhinometry as well as for rhinomanometry, both sensitivity and specificity are higher regarding the prediction of post-operative satisfaction than is the case for anterior rhinoscopy alone [39].

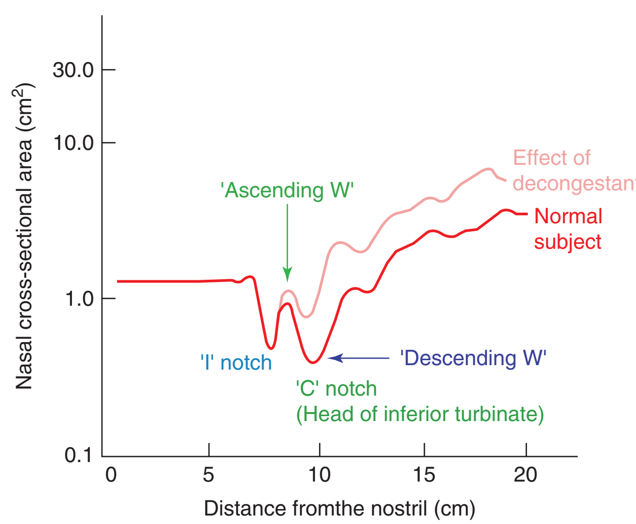

Fig. 11.7 Acoustic rhinometry (Courtesy of Klaus Vogt)

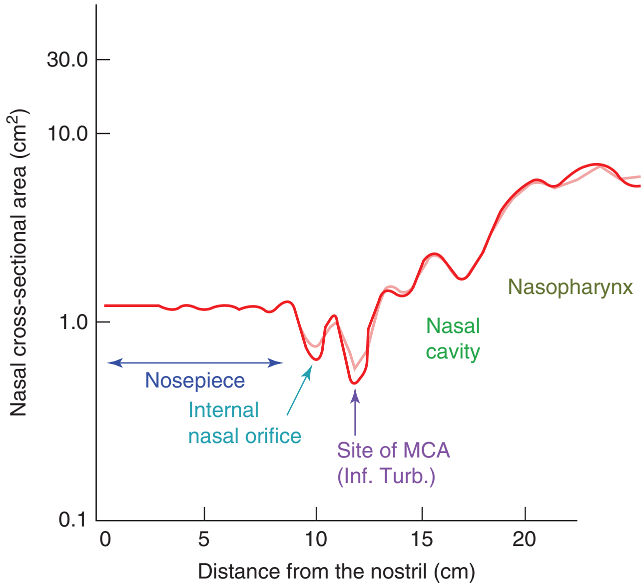

Fig. 11.8 Acoustic rhinometry, nasal cross-sectional area in different distances (Courtesy of Klaus Vogt)

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